ON THE INTERACTION BETWEEN HIGHLY ENERGETIC CHARGED PARTICLES AND THE LUNAR REGOLITH.

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Introduction: The regolith on the lunar surface is exposed to charged particle populations with energies and fluxes typically spanning at least eight orders-of-magnitude and fluctuating with the solar cycle [1]. These populations process the regolith in a variety of ways, including space weathering; electric charging; implantation; chemical alteration; and sputtering, which has implications for the nature of the lunar environment, particularly in permanently shadowed regions (PSRs) [2, 3]. The Lunar Reconnaissance Orbiter's Cosmic Ray Telescope of the Effects of Radiation (CRaTER) [4] is observing the most energetic charged particle populations encountered by the Moon: the episodic solar energetic particles (SEPs) and the ever-present galactic cosmic rays (GCRs). In this study we explore their contribution to the deep dielectric charging of the lunar regolith [5] and surface charging in extremely tenuous plasma environments [3], as constrained by LRO/CRaTER observations.

Charged Particles Incident at the Moon: The three major populations are: the solar wind, SEPs, and GCRs [1]. The solar wind is a continuous quasi-neutral stream of charged particles flowing out from the Sun with relatively low energies ~1 keV nucleon^{-1} (electrons ~10 eV) and high fluxes of ~10^{8} protons cm^{-2} s^{-1}. This intense flux typically only penetrates into the very outer layers of the regolith (~50 nm) and tends to dominate processes at the surface [6, 3; see also Figure 1]. SEPs, also referred to as solar cosmic rays (SCRs), are highly episodic and generally occur more frequently during the solar cycle's declining phase (after solar max). They have energies of ~1–100 MeV nucleon^{-1} (electrons ~0.1–1 MeV) and fluxes of up to ~10^{6} protons cm^{-2} s^{-1}, which can penetrate a few cm into the regolith (only a few mm for heavier nuclei). SEP events are also known to be associated with extreme surface charging of up to ~4 kV negative [7]. GCRs have by far the highest energies ~0.1–<10 GeV nucleon^{-1} and the lowest fluxes ≈ 2–4 protons cm^{-2} s^{-1}, but can penetrate meters into the regolith (cm for the heavier nuclei). Unlike the other populations, GCRs are mostly protons and alpha particles with electrons being only a minor species.

Deep Dielectric Charging by SEPs and GCRs: Since the lunar regolith is a dielectric, i.e. an insulator, and SEPs and GCRs can penetrate it to a range of depths, electric fields will increase within the regolith in response to this accumulation of electric charge. (For comparison, in a good conductor currents would flow in order to neutralize such electric fields.) If the electric charge builds up at a rate faster than it can dissipate, then an electric discharge (breakdown) could possibly occur within the regolith [5, 8]. Such discharges could cause localized melting and the release of a plasma with neutral and ionized constituents, as well as chemical reactions and emission of volatiles [8; 5]. Laboratory experiments have shown that discharges frequently seem to originate in holes, cracks, seams, or at the edges of material (where presumably the electrical stress is larger) [8]. It is therefore plausible that the lunar regolith would have a much greater tendency to discharge than do spacecraft. Even without a discharge, strong electric fields within the regolith may create significant electrostatic stresses on individual regolith grain or induce chemical reactions.

We develop a simple model to approximate these subsurface electric fields. The model's input is a spectrum of isotropically incident charged particles. The typical regolith density profile [9] and the stopping ranges of

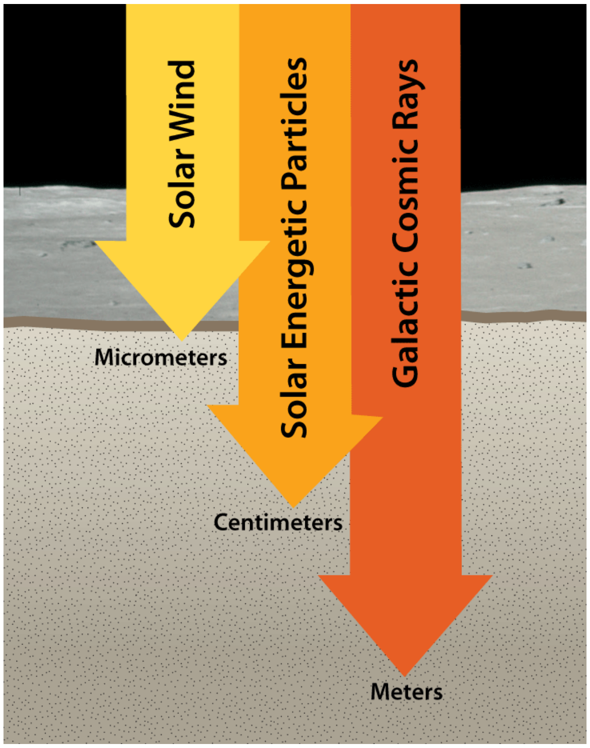

Figure 1: Solar energetic particles and galactic cosmic rays penetrate much more deeply into the lunar regolith than do solar wind particles.

charged particles [10; 11] enable us to estimate the depth to which the particles penetrate. We then calculate the resulting electric field. To model GCRs, we consider only protons. For SEPs, we include both protons and electrons, using their fluxes as observed during the Halloween events in 2003 [12]. Slight departures from charge neutrality in the SEP population for a given penetration depth during these events can create electric fields as shown in Figure 2.

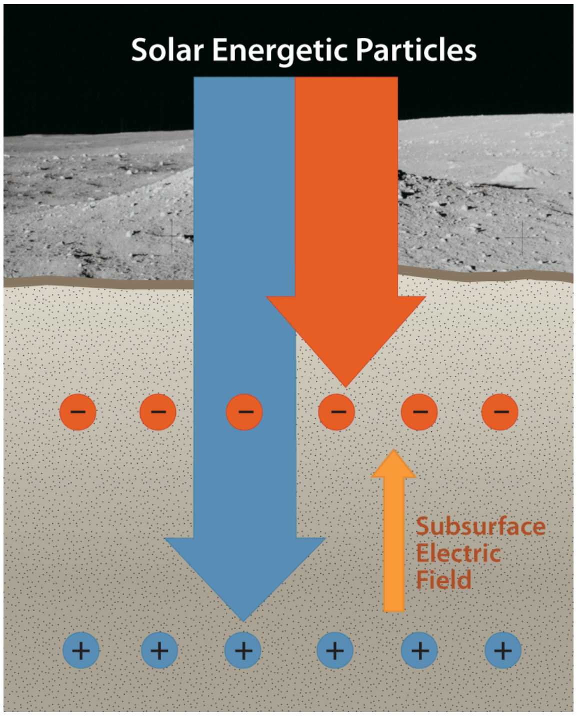

Figure 2: One scenario that can occur during a solar energetic particle (SEP) event is that the bulk of SEP protons penetrate more deeply than the electrons. The reverse scenario could also occur.

GCR Contribution to Surface Charging: Typically the GCR contribution to lunar surface charging is negligible, but under certain circumstances it could become significant. In the solar wind a plasma "void" forms downstream of the Moon, which is referred to as the lunar wake. So called "mini-wakes" associated with topographic features can also form around the terminator and at the poles, and so are relevant to the plasma environment within PSRs [3, 13]. Wake plasmas can be extremely tenuous and it is expected that in some places only the plasma electrons can reach the surface [2]. It has been suggested that the secondary emission of electrons due these incident plasma electrons could be insufficient to provide the anticipated current balance [13], such that there appears to be a "missing" current source. We investigate whether the yield of secondary electrons from GCRs (and the ensuing cascade of particles) could make a significant contribution to this "missing" current. GCRs are isotropic and unaffected by any wake or surface electric fields, and so they have continuous and unimpeded access to the entire lunar surface.

Conclusion: In this study we discover how GCRs and SEPs contribute to deep dielectric charging within the lunar regolith. We also explore how these energetic particles affect lunar surface charging in tenuous plasma environments. Where possible, our models will be constrained by CRaTER observations and associated GEANT simulations. By exploring both charging processes, we will better understand how the lunar radiation environment affects the Moon.

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